VOLUME III

CONCEPTUAL DESIGN

SYSTEM FOR UPPER ATMOSPHERIC SOUNDING (SUAS)

MARCH 1969

PREPARED UNDER CONTRACT NO. NAS1-7911 BY

BOOZ·ALLEN APPLIED RESEARCH Inc.

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LANGLEY RESEARCH CENTER

FOR U.S. GOVERNMENT AGENCIES ONLY

NASA CR-66753-3

VOLUME III
CONCEPTUAL DESIGN

SYSTEM FOR UPPER ATMOSPHERIC SOUNDING (SUAS)

Prepared under Contract No. NAS1-7911 by

Booz, Allen Applied Research Inc.
4733 Bethesda Avenue
Bethesda, Maryland 20014

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

FOREWORD

This study was conducted for the Langley Research Center of the National Aeronautics and Space Administration by Booz, Allen Applied Research Inc., Bethesda, Maryland under Contract NAS1-7911. Mr. T.P. Wright, Jr., of the Flight Vehicles and Systems Division was the LRC Technical Representative of the Contracting Officer. The study was initiated on February 1, 1968 and completed on January 31, 1969.

The study was under the cognizance of Mr. C.F. Riley, Jr. Vice President, of Booz, Allen Applied Research Inc. Mr. W.E. Flowers, Research Director, was the Program Manager. Principal BAARINC staff contributors were Messrs. William E. Brockman, J. Frank Coneybear, Harry L. Crumpacker II, John L. Hain, and David W. Weiss. During the course of the study, Mr. Frederick F. Fischbach of the High Altitude Research Laboratory, University of Michigan, Mr. G. Harry Stine, a private consultant, and Dr. N. Engler, University of Dayton Research Institute, were engaged as consultants.

Reports produced as a result of this study are:

Volume I - Summary Report
Volume II - Technical Report
Volume III - Conceptual Design
Volume IV - Technology Development Plan
Volume V - Program Development Plan.

Volume I is an overview of the project listing results and conclusions.

Volume II is the complete report on the project containing all of the technical analysis.

Volume III is the conceptual design which details the recommended sounding system.

Volume IV is the Technology Development Plan which is an orderly description of the remaining technical problems that need to be resolved prior to system procurement.

Volume V is the Program Development Plan which is an overall plan for the implementation of the system for Upper Atmospheric Sounding.

CONCEPTUAL DESIGN

INTRODUCTION

This document presents the conceptual design of the system for upper atmospheric sounding. The system consists of a launch vehicle, a payload (consisting of a 1-meter, aluminized, inflatable mylar sphere and 1 packet of aluminized chaff), a data acquisition/tracking system and associated ground-support systems.

SYSTEM OBJECTIVES

A system which is capable of probing the atmosphere from 30 kilometers to approximately 100 kilometers for the purpose of obtaining measurements of wind speed and direction, temperature and pressure (or density). The recommended system should be responsive to the requirements for relatively low-cost, high reliability and simplicity of use and be capable of deployment on a worldwide basis.

- The desired system accuracy is:

  temperature---$\pm$ 2° C rms at 30 kilometers
  and not exceeding $\pm$ 5°C rms at 100 kilometers

  wind velocity---$\pm$ 5% rms vector error.

Pressure and density measurements should be consistent with the stated temperature accuracy requirements.

- Operating environment - the system should be capable of deployment on a worldwide basis.

temperature	-40° C to +50° C
humidity	up to 95%
rain	12 inches/hour
wind	up to 60 kts with vehicle on the launcher in hold
	up to 35 kts for launch
salt spray	20% solution.

SYSTEM DESCRIPTION

The system consists of a launch vehicle, a passive payload, a data acquisition/tracking system and associated ground-support systems.

The launch vehicle will loft the payload to an altitude of about 130 km at apogee. The payload contains a 1-meter diameter, aluminized, 1/2 mil mylar, inflated sphere, and about 1 pound of .0006-inch diameter, aluminized plastic filaments or "chaff." The sphere will be deployed at approximately 85 km and coast to apogee, the chaff will be deployed at apogee. The interactions of the sphere and chaff, with the ambient density and winds encountered on its otherwise ballistic-trajectory, will be tracked by an extremely accurate, phased-array tracker/data acquisition system located at the launch site. These measurements will be recorded by the tracking system and will be processed at the launch site (probably) to yield density, pressure, temperature, and horizontal wind vector profiles of the atmosphere between altitudes of 30 km and about 100 km.

SPHERE TECHNIQUE

The sphere is to be tracked by the tracking subsystem and position data recorded. By processing the position data and developing velocities and accelerations along vertical and horizontal axes, the sphere position data is converted to ambient density and wind. The density is derived from the equation for aerodynamic drag:

$$D = \frac{1}{2} C_D A \rho V^2$$

D = drag
C_D = coefficient of drag
A = area
V = velocity
M = mass
ρ = density

Drag is derived from the drag acceleration equation.

$$Ma_d = D$$

a_d = drag acceleration

thus:

$$a_d = \frac{1}{2} C_D \rho V \left(\frac{A}{m}\right)$$

and

$$\rho = \frac{2a_d}{C_D V^2} \left(\frac{m}{A}\right)$$

Temperature can be computed if density is known using the equations of state and of hydrostatic pressure.

$$T_z = \frac{1}{\rho_z} \left[\left(\frac{M}{R}\right) \int_{z_o}^{z} - \rho g \, d z + \rho_o \, T_o \right]$$

where

T_z = ambient temperature
z = altitude
z_o = starting altitude
M = gram molecular weight
R = universal gas constant
g = acceleration of gravity
ρ_o = ambient density at z
T_o = ambient temperature at z_o

typically, the integration of density proceeds downward from the starting altitude z_o, which is the altitude of highest valid density data. The arbitrary choice of ρ_o and T_o at this point may introduce an error in the calculated temperature which, however, decreases and becomes negligible by comparison with other errors at a point about 15 km below the starting altitude.

The measured drag acceleration will be small and difficult to determine from position data. To increase the altitude potential of the system, it is desirable to design the sphere with an $\frac{A}{m}$ as large as possible and to have the velocity in any region as high as practical.

The foregoing considerations have resulted in a substantial effort on the part of experimenters to determine drag coefficients of spheres with great accuracy, to construct spheres from very light material such as .0005-inch thick mylar, and to develop techniques to loft the sphere to an apogee well above the region of interest so that the sphere will have a high velocity during the measurement period. Radar reflective coatings are deposited on the mylar to facilitate tracking.

Due to the nature of tracking subsystems, range data is more precise than angular data. Because of this, more accurate measurements can be made in the most critical accuracy regimes (near the upper altitude limit of measurement) by tracking sphere positions on ascent rather than descent. If the vehicle launcher and tracking subsystem are physically adjacent, as is usually the case, then ascending data will be mainly range measurements while descending data will have substantial angular components.

In order to track the sphere on the ascent leg of the trajectory, it must be deployed just before entering the critical measurement region. If it is deployed early, drag will prevent the sphere from attaining the desired apogee and if too late, the region of interest will be missed.

Ejection and inflation of a very fragile plastic sphere from an aerodynamically-heated container traveling at great velocity through the atmosphere is a difficult design problem, but one that has been largely overcome. Forward ejection of the sphere on the upleg is apt to result in a puncturing of the sphere by the rocket or a rocket component. Rearward or sidewise ejection is indicated.

Inflation will probably be (and is on existing designs) by means of a liquid chemical which vaporizes immediately upon exposure to low pressure. The liquid is contained in a small pressurized vessel within the packaged sphere. The acceleration imparted to the sphere by ejection is utilized to puncture the vessel and allow vaporization (and inflation) to occur.

Ejection will probably be by means of a black powder charge ignited by a dry-cell—timer—squib combination. Detonation of the charge drives the packaged sphere rearward through the payload housing into the atmosphere where inflation occurs. A sabot, which surrounds the sphere, is often used to protect the packaged sphere from aerodynamic heating, hot ejection gas, and ejection friction.

CHAFF TECHNIQUES

Chaff is designed with an $\frac{A}{m}$ ratio as large as possible for the same reasons that dictated a high $\frac{A}{m}$ ratio for the sphere. Chaff can be manufactured in the shape of very fine filaments (.001 inch or less) or thin flat ribbons. In either case, the surface must be coated with an electrical conductor or the chaff material must be an electrical conductor, to permit radar tracking. The length of the chaff is made to correspond with a dipole length of the radar frequency. Chaff can be made with an $\frac{A}{m}$ ratio about one order of magnitude greater than that of an uninflated sphere; therefore, it has a potential for measuring atmospheric motion higher in the atmosphere than a sphere. There are many drawbacks with the use of chaff. Since the individual pieces have random orientations, the chaff falls with different drag accelerations and eventually the "cloud" disperses into a column. When tracked with a radar device, the exact position of the cloud is difficult to determine because the size and shape of the target is not predictable and is ever changing. As a result of the tracking difficulty, precise double differentiation of position data is impossible. The random orientation makes assignment of an accurate drag coefficient impossible. For these two reasons, chaff is not used to determine density. The determination of high-altitude winds, however, over a vertical layer of considerable size, is feasible with chaff. The favorable $\frac{A}{m}$ ratio causes the chaff to experience more displacement due to horizontal winds than that attainable by a sphere. This fact permits winds to be measured to a greater altitude, given the same tracking capability.

Chaff will be ejected from the payload container near apogee with sufficient force to separate the individual pieces into a cloud but not enough to disperse the cloud into an imperceptible radar target. Ejection will be accomplished under (essentially) vacuum conditions. The optimum ejection technique for this application must be developed experimentally.

LAUNCH VEHICLE

Many candidate vehicles are available which are capable of placing the small payload at an apogee of about 130 km. Analysis of performance and cost projections has shown that a rocket or a rocket-boosted dart have a cost advantage over competing launch concepts. The rocket system is a long-burning rocket motor. Burnout occurs sufficiently high that drag is unimportant for the remainder of the flight. The rocket-boosted dart system employs a high-thrust, short-burning rocket booster with a low-drag, detachable payload container (or dart) which coasts to apogee. The cost trade-offs between the two systems are close and the choice should be decided in a competition between manufacturers.

THE ROCKET SYSTEM

The long-burning rocket will have an impulse requirement on the order of 24,000 lb/sec. A higher launch acceleration may be required to overcome wind sensitivity. It could be provided by a detachable booster or a short-burning, propellant grain added to the main motor (dual thrust). A fin-stabilized rocket meeting these requirements would be about 6 inches in diameter, 8 feet long and weigh about 150 pounds.

THE ROCKET-BOOSTED DART SYSTEM

The rocket-boosted dart system consists of a high-thrust, short-burning rocket with a total impulse in the neighborhood of 41,000 lb/sec. A booster meeting these requirements is expected to be slightly larger in size than the slow-burning rocket motor. The size of the dart required to house the payload could be on the order 2 inches diameter and 4 to 5 feet in length. It will have a payload volume of approximately 100 cubic inches. Fins will be required for both the booster and the dart. The payload will require ballast. Acceleration levels with this system will be in the neighborhood of 50 g.

Aerodynamic heating of all critical surfaces, e.g., payload container and fins, will be controlled by the application of an ablative material. Fin-leading edges may require structural reinforcement by high-melting point metal such as inconel.

LAUNCH SUBSYSTEM

The requirements of the launcher are straightforward and designs are plentiful. The launcher cannot be designed until after the rocket design is completed. Launcher constraints should play no important part in the vehicle design.

DATA ACQUISITION/TRACKING SYSTEM

The basic requirement for the data acquisition/tracking system is to develop a position versus time profile for the chaff and the sphere.

The block diagram of the data acquisition/tracking system is shown in Figure 1. The heart of the subsystem is a general-purpose digital computer. Upon receipt of a lift-off signal from the launcher, the computer will command the transmit array to illuminate a sector to intercept the ascending vehicle at a predetermined altitude. The pulse repetition rate will be set to permit unambiguous ranging on the reflected signal. Simultaneously, a cluster of receiving beams will be formed in the same sector. Automatic angle tracking of the vehicle will be initiated when a predetermined number of sequential receiver pulses cross the 10 db threshold. Ejection and inflation of the sphere will produce two targets exhibiting markedly different reflective characteristics. A pair of displays will permit the operator to select the one corresponding to the sphere, and range tracking (along with velocity determination) will be initiated.

The computer will continue to steer the transmitted beam in such a direction as to keep the sphere illuminated. It will simultaneously form a monopulse quad beam at the receiver to ascertain the instantaneous line-of-sight to the sphere. Beam-splitting techniques will be used to increase the angular resolution by 20:1. The interval between pulses will be gradually increased as the range increases to

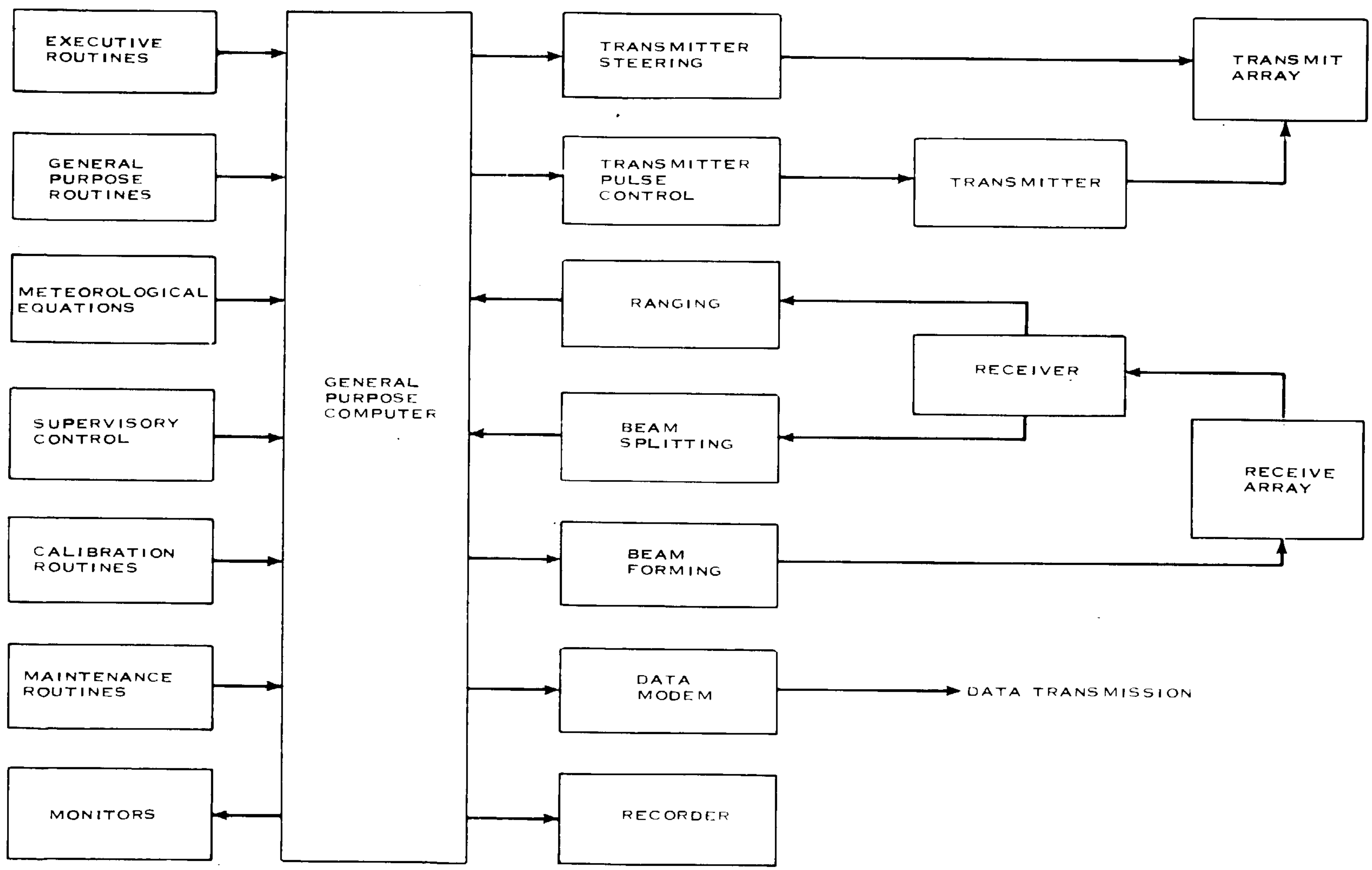

FIGURE 1. Data Acquisition/Tracking System

ensure nonambiguous readings. As the sphere velocity becomes very low, the redundancy in readings will become considerably in excess of that which is useful in achieving requisite accuracy in density profile and wind vectors, so the pulse spacing may be increased.

The system will also simultaneously track the ascending vehicle until the release of chaff. The chaff will be tracked like the sphere. The phased-array tracker will be housed in a one-story building with the planar antenna lying flat on the roof. A tilt of the roof equal to that of the launcher's nominal inclination will be required. The arrays themselves will be solid-state, integrated-circuit units assembled on automated assembly lines. The transmitter units will include the final power amplifier, the steering elements, and the radiating elements. The receiving units will include the radiating elements, the low-noise receiver front ends, and the beam-forming matrices. The range tracker will be an early-gate/late-gate, solid-state digital tracker.

The circuitry lends itself to mass production techniques. Complete subassembly and checkout will be conducted in the factory. The on-site activity will be limited to installation, plug-in, and calibration. The design will include full maintenance and calibration routines under computer program control so as to permit operation and maintenance by personnel of minimal skills.

The most critical part of the tracker is the receiving array. It will require about 10,000 identical elements packaged into convenient modular subassemblies.

The phased-array tracker offers two inherent advantages over an electromechanical tracker. Acquisition is far less of a problem since scan patterns may be implemented in microseconds in lieu of seconds, and multiple target tracking is much more readily attained. Both characteristics are useful in the synthesis of this sounding system. The facile acquisition capability minimizes the need for skilled operating personnel and the need for backup vehicles. The multiple target tracking capability eases the transfer of track from the aerodynamic vehicle to the inflated sphere, thus, further minimizing the need for skilled operators and backup vehicles.

A brief look at how a phased array functions will show how these characteristics arise. They may then be related to the operational aspects of the sounding system. A simple linear dipole has a broad directional pattern as shown in Figure 2. Locating two or more radiating elements close to each other will result in an effective adding of their radiated power in the far field; that is, at some distance from the antennas. If all antennas are driven in phase, the effective beam width is narrowed in proportion to the number of antennas, see Figure 3. If, however, these antennas are driven not in phase, but rather with an integral incremental phase shift, the beam will tend to retain its narrowed contour but be reoriented off the axis of the array. A practical method of steering such an array is shown in Figure 4. A tapped delay line provides the uniformly incremental phase shifts to be inserted between the transmitter and the antennas. The amount of shift and the size of the angle steered off axis is determined by the steering frequency since the phase shift of a real delay line is a function of frequency. The steering frequency itself is removed from the transmitter frequency by post-delay line mixers, thus permitting narrow band operation. Antenna reciprocity permit comparable beam forming on received signals.

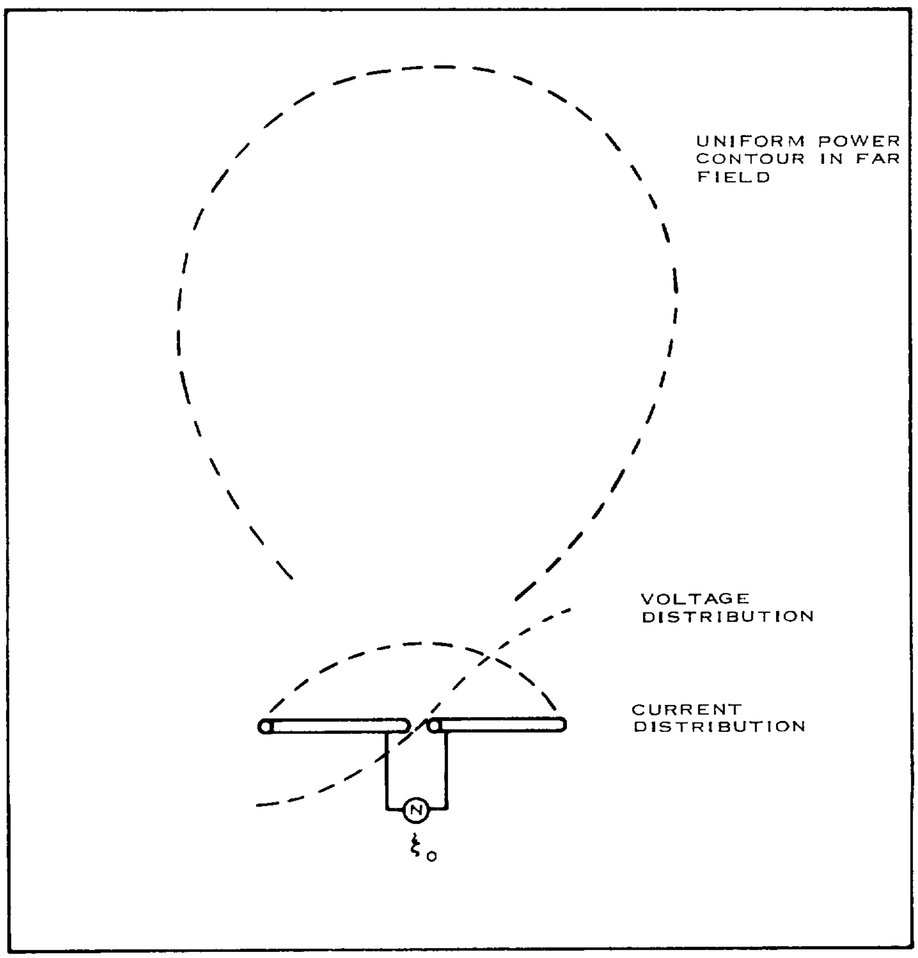

FIGURE 2. Simple Dipole

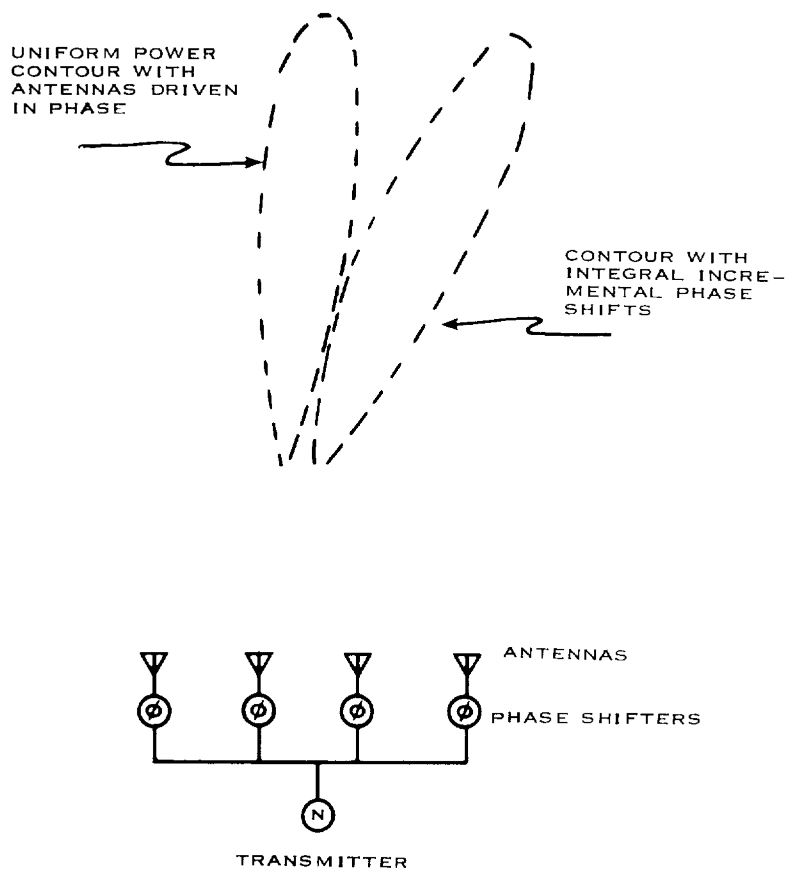

FIGURE 3. Phase Shifted Array

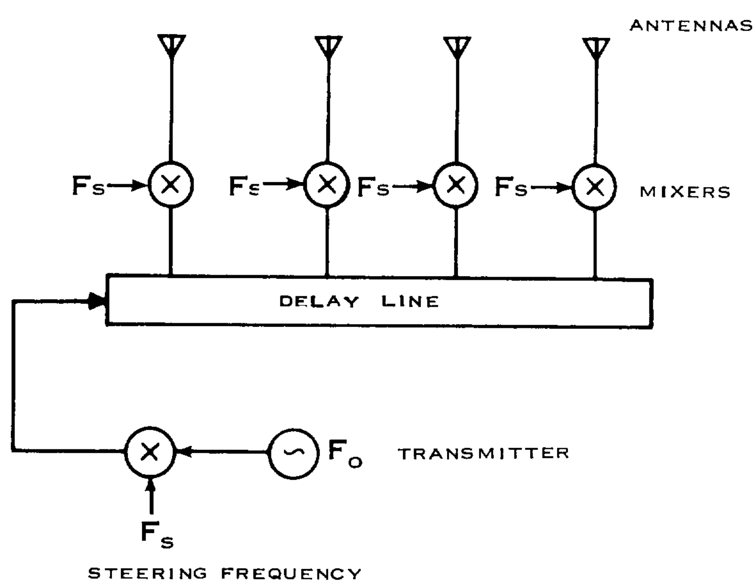

FIGURE 4. Typical Steering Technique

Since a stable frequency synthesizer operating under the control of a digital computer can steer transmitted beams to any point within the tracker field of view at a speed limited only by the input/output capabilities of the computer, illumination of widely varying sectors can be accomplished at will, reducing the acquisition problem to a trivial one. The fact that two or more such sectors may be illuminated in sequence at a rate which produces the effect of simultaneity permits received beams to be formed on two or more targets with simulataneous readouts. Thus, track of all components of the lofted package may be maintained until positive identification of the sphere is established.

During the tracking operation some degree of adaptive control pulse spacing and real-time prediction and data smoothing will be performed by the computer. After flight termination, the recorded tracking data may then be batch processed by the same computer to extract the requisite meteorological data: pressure, temperature, wind velocity, and wind direction. These data may then be formatted for facile transmission, and actually transmitted to the control center for synoptic use.

PERFORMANCE SPECIFICATIONS

PAYLOAD

Sphere

Reliable inflation to spherical shape within 2% on any diameter

Sufficient overpressure to remain spherical from a vacuum to 10 mb external pressure for 10 minutes

Diameter not less than 1 meter

Weigh not more than 150 grams including inflation gas

Radar reflecting aluminized surface

Packaging dimensions: maximum diameter 38 mm
maximum length 46 cm.

Chaff

Plastic filaments with radar reflective coating not to exceed .0006 in diameter. Alternative: Rectangular shaped, radar reflective coating on 2 surfaces, not to exceed .0006 inches in one dimension and .0048 inches in the other. Cut to S-band dipole length $\pm$ 1 mm.

Material not to exceed density of 1.5 gms/cc

Packaging dimensions: same as sphere

Weight: not less than 450 gms.

Operations

Sphere to be ejected at preset time $\pm$ 1 second.

Sphere to be ejected at 30 meters/second $\pm$ 5 m/s

Sphere to be ejected rearward or to the side with no mechanical part to be directly aft of the sphere

Chaff to be ejected at preset time $\pm$ 5 seconds.

Chaff orientation to be essentially undisturbed by ejection technique

Ejection mechanisms not to exceed 1 kg and 200 cc.

Environment

Storage of packaged payload for 1 year

Any items requiring assembly to be done by 1 man in less than 30 minutes

Storage conditions: Dry, $-40^{\circ}C$ to $+50^{\circ}C$

Package to be fully operative to $-70^{\circ}C$

Linear acceleration not to exceed 150 g's.

LAUNCH VEHICLE AND PAYLOAD CONTAINER

Performance

At effective launch angle of 85° Q. E., place payload at an apogee of not less than 130 km nor more than 140 km (from sea level launch).

Linear acceleration not to exceed 135 g's

Interior surface of payload container not to exceed 60°C

Apogee performance not to deviate from design specification more than 1° and 5 km.

Launch acceleration not less than 15 g's

Payload container to remain aligned with tangent to trajectory within 10° to 85 km.

Environment

Storage for 2 years at -40°C to + 50°C

Transportation and vibration typical MIL Specs

Reliable operation at -40°C to 50°C. (May be conditioned for optimum performance.)

LAUNCHER

Performance

Provide rail guidance for 10 feet

Deflect less than 1° in launch elevation plane and cross plane under 200-pound load at tip of rail

Adjust readily up to ± 85° in elevation and ± 45° in azimuth.

Provide for underside loading of launch rail in horizontal position of no more than 5 feet above ground.

Elevate from horizontal to 85° Q.E. in less than 1 minute.

Operation from -40°C to + 50°C (special equipment may be provided for cold weather operation).

Environment

Operate without regard to rain, snow, and icing conditions or other adverse climatic conditions.

DATA ACQUISITION/TRACKING SYSTEM

Performance

Tracking - multiple targets (1-5) tracked simultaneously, acquisition of rocket before separation (initial track of the launch vehicle with simultaneous track of smaller targets as they separate from the rocket and become distinguishable due to range and/or angular separation), all targets within same 20° cone of total coverage.

Accuracy - $\pm$ 0.2 milliradian angular, $\pm$ 5 meters range (1σ values, $\pm$ 20 degrees of boresight, 1 hit 160 km, range, data rate of 1 point per 2 milliseconds, 1 square meter target).

Range - 200 km maximum

Coverage - 60° cone around a fixed boresight

Operation - all-weather, minimum technical attendance.

Characteristics

S-band, phased-array, one face

High-duty cycle -$\sim$40 percent

Prepacked for simple on-site installation with minimum checkout and test

Solid-state, modular automatic fault isolation for plug-in maintenance

Built-in, general-purpose digital computer

Initial on-site calibration may require appreciable use of equipment and personnel

Routine calibration fully automated.

Transportation and vibration limits to typical MIL Specs

Payload to be fully operative after 5 minutes in a 10^{-5} torr vacuum (since ejection/inflation will occur in a near vacuum).